frontiers | Frontiers in Soil Science

TYPE Review
PUBLISHED 19 August 2025
DOI 10.3389/fsoil.2025.1624486

OPEN ACCESS

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RECEIVED 07 May 2025
ACCEPTED 22 July 2025
PUBLISHED 19 August 2025

CITATION
Quansah KE, Asah-Asante R, Xudong F, Xinran S, Ming L, Di W, Xin M, Jizhong W and Miao G (2025) Vegetable residue valorization for soil health and climate resilience. *Front. Soil Sci.* 5:1624486. doi: 10.3389/fsoil.2025.1624486

Vegetable residue valorization for soil health and climate resilience

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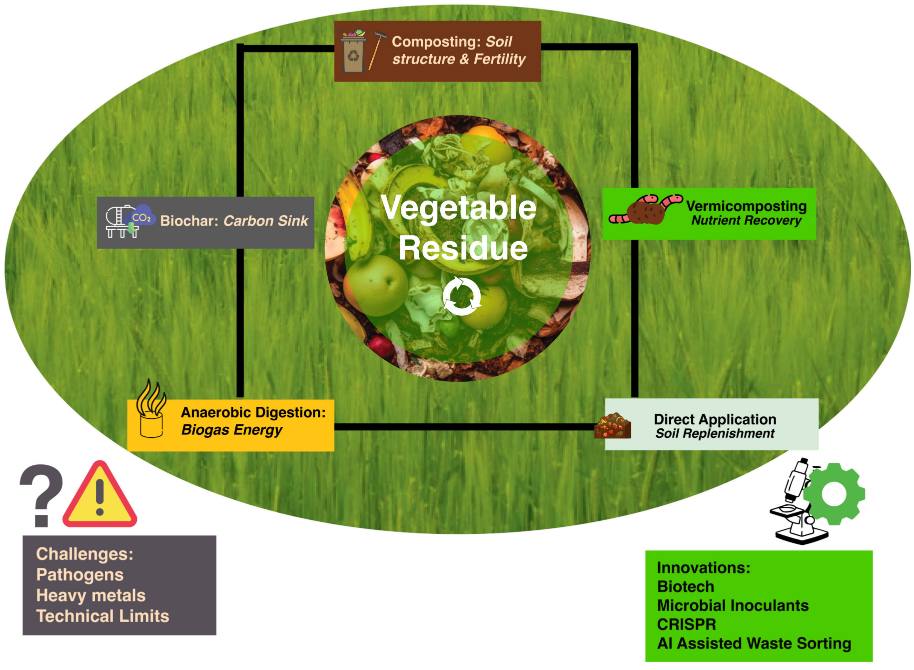
Food waste is a critical global challenge that threatens environmental sustainability. Vegetable residue, a key component, is often disposed through harmful methods such as landfilling and incineration which significantly increase resource loss and degrade the ecological system. Sustainable and eco-friendly valorization techniques are solutions needed to address this challenge. This review explores the valorization of vegetable residue within a circular agriculture framework, emphasizing its potential to enhance soil health, reduce reliance on synthetic fertilizers, and support climate resilience. Vegetable residues, rich in organic matter, can be valorized through composting, vermicomposting, anaerobic digestion, biochar production, direct application, or integrated system (biochar + compost) to produce nutrient-rich soil amendments and renewable energy. These approaches enhance soil fertility, microbial activity, water retention, and carbon sequestration. However, challenges persist, including heavy metal contamination, technical constraints, and adoption barriers. Recent advances, such as microbial inoculants, enzyme-based pretreatment, integrated residue management systems, and emerging AI and low-energy technologies offer promising solutions to address these limitations. This review systematically synthesizes current practices, emerging innovations, and policy frameworks to advance sustainable residue utilization and agricultural transformation.

KEYWORDS

vegetable residue, soil health, circular agriculture, climate resilience, residue management



GRAPHICAL ABSTRACT

1 Introduction

The rapid global population expansion, projected to reach 9.1billion by 2050 (a 34% increase), coupled with growth in industrialized agriculture, has resulted in a large amount of food residue generation, particularly vegetable residue, posing serious environmental problems (1). Food security, soil deterioration, and environmental pollution are pressing challenges that require the agricultural sector to shift to sustainable practices (2). Ecosystem health and long-term agricultural production are seriously threatened by conventional farming techniques that rely primarily on synthetic fertilizers and intensive land use, which greatly increase soil erosion, nutrient depletion, and water contamination (3). Circular agriculture, which prioritizes resource efficiency, residue recycling, and nutrient recovery, has become a practical strategy for maintaining agricultural sustainability (4).

Globally, around 1.3 billion tons of edible food are wasted annually, ending up in landfills and contributing to greenhouse gas emissions, environmental degradation, and an estimated $990 billion in economic losses across developed and developing nations (5, 6). Vegetable residues, which contributes 40–50% of edible food waste (7), offer a sustainable alternative to synthetic fertilizers due to their high organic matter content and essential nutrients like nitrogen (N), potassium (K), and phosphorus (P) (7, 8). By converting these residues into soil supplements, we can enhance nutrient cycling and improve soil quality, addressing both waste management challenges and advancing the principles of circular agriculture (9).

Composting, anaerobic digestion, vermicomposting, biochar formation, direct application, and integrated system (biochar + compost) are methods used in agriculture to use vegetable residue. By transforming the residue into stable, nutrient-rich forms, these activities can enhance microbial activity, water retention, and soil fertility. Compost made from vegetable residue, for example, has been shown to boost cation exchange capacity, boost soil organic carbon levels, and sustain beneficial microbial populations (10). The pyrolysis of organic residue can also produce biochar, which can improve the soil structure and the availability of nutrients while serving as a long-lasting carbon sink (11). Vegetable residues contribute 58% of U.S. landfill methane (7, 12). Composting these residues reduces methane emissions by 38–84% while improving soil CEC by 20–40% (12, 13).

This review targets smallholder and peri-urban agricultural systems, excluding large-scale municipal facilities due to their fundamentally different infrastructural requirements and operational scales. We focus on practical, scalable solutions that can be implemented in resource-constrained settings while maximizing environmental and agronomic benefits.

Abbreviations: AD, Anaerobic Digestion; ABC, Agricultura de Baixo Carbono; CEC, Cation Exchange Capacity; C: N, Carbon,to,Nitrogen ratio; EPA, Environmental Protection Agency; SOM, Soil Organic Matter; VFAs, Volatile Fatty Acids; MSR, Municipal Solid Residue; PW, Press Water; RMSE, Root Mean Square Error; IPCC, Intergovernmental Panel on Climate Change; CEA, Controlled Environment Agriculture; R&D, Research and Development; SMEs, Small and Medium,sized Enterprises; AI, Artificial Intelligence; EU, European Union; CRISPR, Clustered Regularly Interspaced Short Palindromic Repeats; IRMS, Integrated Residue Management Systems.

2 Scientific approaches for utilizing vegetable residue

2.1 Direct application

The direct application of vegetable residue to soil enhances fertility by promoting microbial-mediated nutrient cycling, where decomposers like *Bacillus* (Table 1) and *Trichoderma* break down cellulose, while nitrogen-fixing (*Nitrosomonas*) and phosphate-solubilizing bacteria (*Pseudomonas;* Table 1) convert organic matter into plant-available nutrients (14). Residue composition influences nutrient release low C:N ratios (e.g., leafy greens) mineralize nitrogen rapidly, whereas high C:N materials (e.g., woody stems) may temporarily immobilize nitrogen, requiring pre-composting (15). Lignin-degrading fungi contribute to humus formation, improving soil stability, while microbial exopolysaccharides enhance aggregation, reducing reliance on synthetic fertilizers and suppressing pathogens (16). Challenges like nutrient immobilization or allelopathic effects (e.g., onion/garlic peels) can be mitigated through controlled decomposition, aligning with circular agriculture by closing nutrient loops (17).

2.2 Composting

Composting is a vital practice in sustainable agriculture, enhancing soil fertility by improving organic matter content, nutrient availability, and microbial activity, which collectively boost soil structure, water retention, and plant productivity (Figure 1) (14, 18–20). The decomposition process is driven by dynamic microbial communities, including bacteria (*Bacillus subtilis;* Table 1), fungi, and actinomycetes, whose activity is optimized at a carbon-to-nitrogen (C:N) ratio of ~30:1, ensuring efficient breakdown while minimizing odor and nutrient imbalances (21). Key operational factors such as aeration (maintaining aerobic conditions), moisture (50–60%; Figure 2), and residue composition (Table 2) critically influence composting efficiency (22). Beyond agronomic benefits, composting mitigates environmental impacts by diverting organic waste from landfills, reducing greenhouse gas emissions (23, 24).

Composting performance is critically influenced by feedstock composition, particularly the carbon-to-nitrogen (C:N) ratio and moisture content, which govern microbial metabolic activity and heat generation. High-moisture, nitrogen-rich vegetable residues often induce anaerobic conditions due to excessive water retention, slowing decomposition and promoting foul odors (14). Conversely, lignocellulosic bulking agents such as maize straw (C:N ~60–80:1, moisture <15%) or dry leaves (C:N ~40–60:1, moisture 10-20%) provide structural porosity, enhance oxygen diffusion, and balance excess nitrogen (25). Research demonstrates that blending these feedstocks in ratios achieving an initial C:N of 25–30:1 significantly accelerates microbial colonization, with thermophilic bacteria like *Bacillus* spp., *Thermus* spp. proliferating rapidly, driving composting temperatures to 55–65°C within 48 hours (26). A study by Finore et al. found that a 3:1 ratio of vegetable residue to maize straw reduced composting time by 40% compared to unmixed vegetable residue, while maintaining >55°C for 5 (+) days, ensuring pathogen inactivation (EPA Class A standards) (27). Moisture optimization (50–60%) through bulking agents prevents leachate formation and enhances lignin degradation by thermophilic fungi like *Aspergillus fumigatus* (28). Strategic blending thus offers a scalable solution to improve composting kinetics, reduce greenhouse gas emissions, and yield stable, nutrient-rich compost (29).

2.3 Vermicomposting

Vermicomposting enhances soil fertility and agricultural productivity by promoting nutrient cycling, microbial biodiversity, and humic substance formation through earthworm-mediated decomposition of organic matter (10, 30–32). Vermicompost increases the bioavailability of essential nutrients (N, P, K; Table 1) and improves soil structure by accelerating organic matter breakdown into plant-accessible forms (33). According to studies conducted by Blouin et al., application of vermicompost increases plant biomass significantly, with average increases of 26% in commercial yield and 78% in microbial biomass (34). Its humic compounds and microbial communities (*Pseudomonas putida*; Table 1) further enhance soil ecosystem functioning, microbial biomass, and long-term fertility (35–38).

2.4 Anaerobic digestion

Anaerobic digestion (AD) of vegetable residue is a four-stage biochemical process (hydrolysis, acidogenesis, acetogenesis, and methanogenesis; illustrated in Figure 2) mediated by specialized

TABLE 1 Key microorganisms in vegetable residue decomposition and their roles.

Microorganism	Decomposition role	Process involved	Optimal condition	Reference
Bacillus subtilis	Cellulose degradation	Composting and Direct application	pH6.5–7.5, 30°C–37°C	(14)
Trichoderma spp	Lignin breakdown	Biochar	Aerobic, mesophilic range.	(53)
Pseudomonas spp	Phosphate solubilization	Direct application	Moist, neutral pH	(68)
Methanobacterium spp	Methane production	Anaerobic digestion	Anaerobic,35–40°C	(39)
Pseudomonas putida	Phosphate solubilization	Vermicomposting	25–30°C, moist substrate	(32)

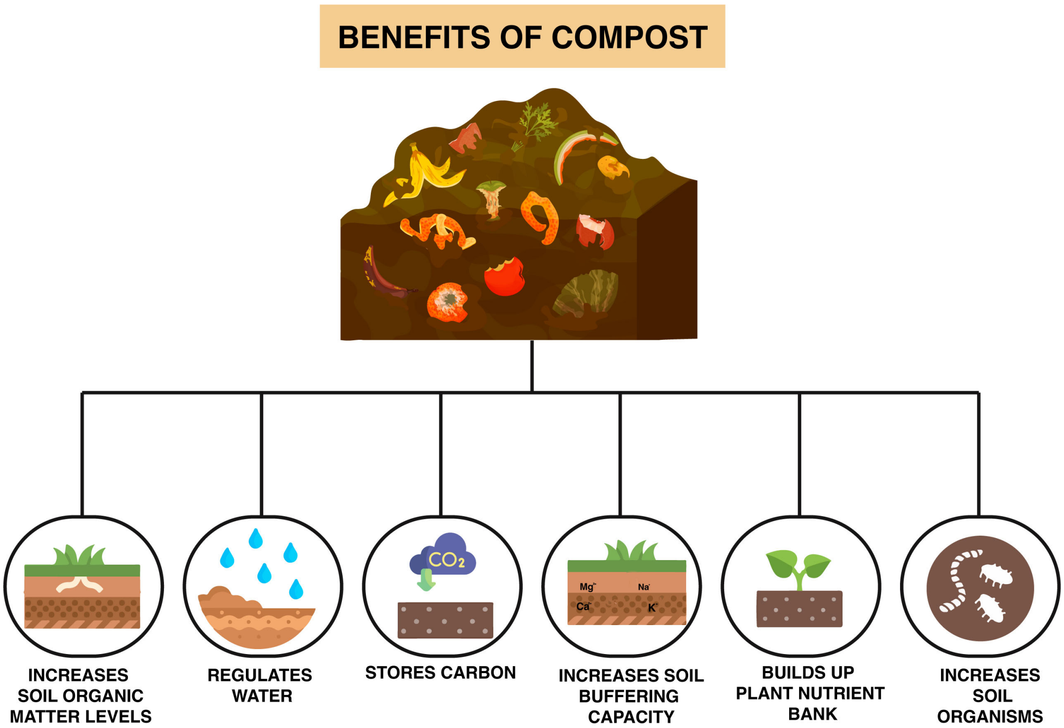


FIGURE 1
Benefits of compost, highlighting its role in improving soil quality and plant growth.

microbial communities to produce biogas (CH_4 and CO_2) (39, 40). Hydrolysis, the rate-limiting step, breaks down recalcitrant cellulose and hemicellulose via extracellular enzymes from *Clostridium* and *Bacteroides* spp., with enzymatic pretreatments often required to enhance efficiency (32, 41, 42). Acidogenic bacteria (e.g., *Clostridium*, *Enterobacter*) ferment monomers into volatile fatty acids (VFAs), while acetogens (e.g., *Syntrophobacter*) further convert VFAs to acetate, H_2, and CO_2, critical substrates for methanogenesis (43–46). Methanogenic archaea (e.g., *Methanobacterium* spp.; Table 1) then produce methane, with process efficiency dependent on substrate composition, microbial dynamics, and operational conditions (pH, temperature, retention time) (47–50). AD offers

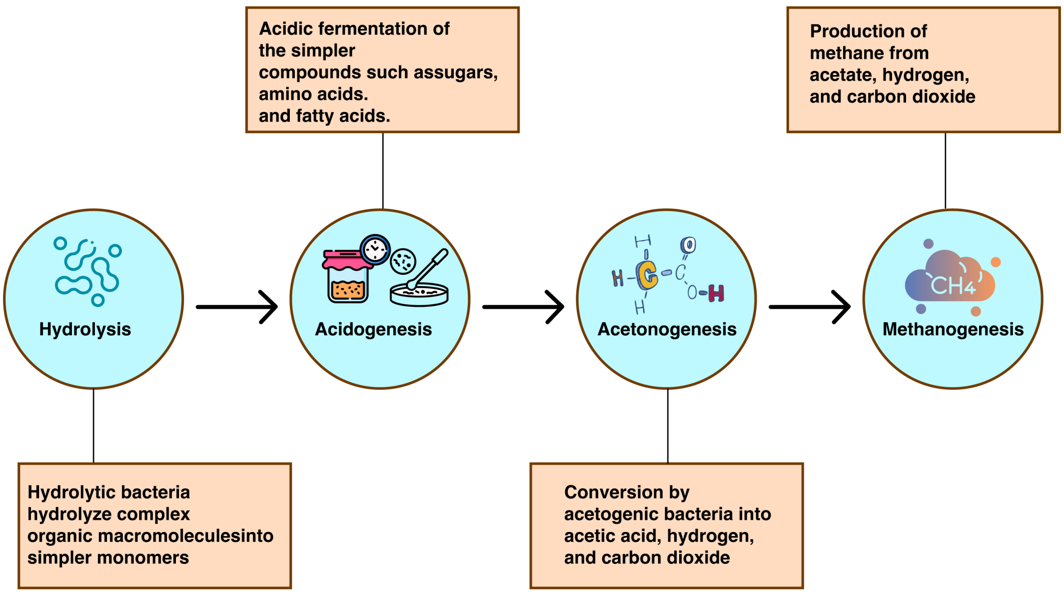


FIGURE 2
Biochemical processes of anaerobic digestion.

TABLE 2 Comparative analysis of vegetable residue utilization techniques.

Technique	Composting	Vermicomposting	Anaerobic digestion	Biochar production	Direct application	Integrated system (Biochar + Compost)
Complexity	Moderate (requires monitoring of C:N ratio, moisture, and aeration).	Moderate, i.e., requires controlled conditions (temperature, moisture, and species).	High, i.e., requires controlled conditions (pH, temperature, and microbial communities).	Moderate, i.e., requires temperature control and specialized pyrolysis equipment.	Low, i.e., requires simple incorporation into the soil.	
Energy Balance	Neutral, i.e., requires no external energy input but employs aeration.	Neutral, i.e., no significant amount of energy inputs required.	Positive, i.e., produces biogas.	Variable, i.e., depending on the pyrolysis system, can be positive or negative.	Neutral-positive, i.e., minimal input of energy.	Synergistic benefits
Cost	Low–moderate cost for equipment and labor.	Low–moderate, i.e., requires worm beds and maintenance infrastructure.	High, i.e., capital intensive for reactors and handling of gas.	High, i.e., requires high cost of pyrolysis units and feedstock preparation.	Very Low, i.e., no, or minimal cost of processing.	Varies
Policy needs	Residue diversion laws	Standard quality	Carbon credits	Extension programs	Feed-in tariffs	R&D incentives.
Suitable for	Most farm sizes	Peri-urban and organic farms	Carbon farming	Small farms	Commercial farms	Large-scale operations
Risk	Low pathogen risk if properly managed.	Low–moderate, i.e., quality of feedstock, sensitivity of temperature and risk of pests if not properly managed.	Moderate, i.e., odor, instability in procedure and toxic byproducts.	Low. (Polluted feedstock can cause heavy metal contamination.	Moderate, i.e., pathogen survival, phytotoxicity and nutrient leaching.	Moderate (depends on system design)
Nutrient Recovery	High, i.e., enhances soil fertility, release of NPK and microbial activity.	Very high, i.e., improves microbial activity, produces vermicast rich in nutrients and improves humus content.	Moderate to high, i.e., recovers adequate nutrients but with possible NH_3 loss.	Moderate, i.e., locks up nutrients in stable states, improves CEC and immobilizes nitrogen temporarily	High, i.e., availability of rapid nutrients; risk of Immobilization of Nitrogen with high C: N ratio.	High (synergistic nutrient retention).
GHG reduction	Moderate, i.e., reduces landfill methane but may emit CO2 and N2o during decomposition.	Moderate–high, i.e., reduces methane from landfills if well managed.	High, i.e., reduction of methane emissions from landfills and displaces fossil fuels.	Very High, i.e., reduces N_2O emissions and long-term carbon sequestration.	Low–moderate, i.e., no processing emissions, but may release methane and N_2O if raw material decomposes.	High (combined carbon sequestration and emission reduction)
Reference	(57, 58)	(17, 59, 60)	(61)	(62, 63)	(64, 65)	(66, 67)

sustainable organic residue management and renewable energy generation, though optimization is needed for consistent biogas quality and integration into energy systems (25, 51, 52).

2.5 Biochar production

The thermochemical conversion of vegetable residue into biochar via pyrolysis a process involving oxygen-limited heating (100–500+ °C) yields a carbon-rich material with applications in carbon sequestration, soil enhancement, and contaminant adsorption (53, 54). Biochar properties (e.g., porosity, functional groups, stability) depend on pyrolysis conditions (temperature, heating rate, residence time), with higher temperatures favoring carbonization and lower temperatures retaining oxygenated groups for nutrient interactions (55, 56). Its use in soils improves water retention, nutrient availability, and microbial activity (*Trichoderma* spp.; Table 1) while mitigating greenhouse gases through carbon stabilization and reduced N_2O emissions (37, 53). Additionally, biochar effectively adsorbs heavy metals (e.g., Pb, Cd, As) and organic pollutants in wastewater, aligning with circular agriculture by diverting residue from landfills (75, 76).

3 Benefits of returning vegetable residue to soil

3.1 Soil fertility improvement

The return of vegetable residues to the soil enhances soil fertility through improved nutrient availability and increased microbial activity, as demonstrated by studies showing that crop residue incorporation, such as tomato biomass, boosts soil organic carbon (SOC) and stimulates beneficial soil biological processes essential for nutrient cycling and crop productivity (Figure 3) (69). Although residue incorporation can raise nitrous oxide (N_2O) emissions by approximately 29.7%, it also reduces nitrate leaching by 14.4%, depending on soil conditions, while compost amendments (10–20 Mg ha^{-1}) increase cation exchange capacity (CEC) by 20–40%, significantly reducing nutrient leaching losses (30–50%) without depleting plant-available nutrients (16). Moreover, residue return enhances microbial biomass carbon and enzymatic activity, leading to higher crop yields (70), with organic amendments like compost and manure increasing dehydrogenase, cellulase, and urease activities by up to 7.5, 6.8, and 17.9 times, respectively, compared to untreated soils, highlighting the vital role of organic matter in sustaining soil health and agricultural productivity (71, 72).

3.2 Organic matter enrichment

Incorporating organic matter into soil systems is essential for improving microbial activity, soil structure, and water retention all of which promote resilient ecosystems and sustainable farming methods (25). OM serves as a nucleus for soil aggregate formation, reducing bulk density by up to 12% and increasing porosity by 15–30%, thereby facilitating gas exchange and root proliferation (73). The stabilization of carbon varies by treatment, with lignin-rich biochar retaining 90% of carbon over centennial timescales, compared to 40–60% for compost (74). These improvements correlate strongly with aggregate stability ($r^2 = 0.78$, $p < 0.001$) and microbial enzymatic activity, underscoring the role of organic matter in soil structure and fertility (Figure 3) (75). In the soil ecosystem, the addition of organic matter also promotes microbial activity and multiplication. Microbial communities thrive in residue-amended soils, accelerating nutrient mineralization and promoting disease-suppressive properties (55, 76).

3.3 Climate change mitigation

Methane (CH_4) has a global warming potential around 25 times that of carbon dioxide (CO_2) over a 100-year period, so reducing methane emissions from landfills is essential (47). Composting diverts organic waste from landfills, cutting methane (CH_4) emissions by 38–84% (77). Anaerobic digestion of residues further mitigates 0.25–0.50 kg CH_4 per kg volatile solids (57). When converted to biochar, vegetable residues reduce N_2O emissions by 30–80% in nitrogen-rich soils by inhibiting microbial nitrification. Integrated biochar-compost systems sequester 2.8–4.2 Mg CO_2-eq/ha/yr, with additional energy recovery through 120–150 m^3 CH_4/ton of residue (78). Biochar-amended soils show a 78% increase in SOC, offering long-term carbon storage. These practices align with natural climate solutions, potentially delivering 37% of cost-effective CO_2 mitigation needed by 2030 (see Figure 4 for conceptual framework) (79).

3.4 Residue management solution

The scale of vegetable residue generation presents both a challenge and an opportunity for sustainable residue management. Post-processing residues including peels, seeds, and pomace contribute 20–30% of total agro-industrial waste, with improper disposal leading to significant environmental consequences (80–82). When landfilled, these residues decompose anaerobically, emitting 50–100 m^3 of methane (CH_4) per ton, a greenhouse gas with 28–36 times the global warming potential of CO_2 (49, 83).

Anaerobic digestion of vegetable residues yields 0.25–0.45 kWh of biogas per kg, offering a renewable alternative to fossil fuels (78, 84, 85). Beyond energy recovery, agricultural residues such as potato peels have demonstrated 80–95% adsorption efficiency for heavy metals (Pb^{2+}, Cu^{2+}) in wastewater treatment, presenting a low-cost biosorption solution (73, 86–90). Heavy metal contamination, particularly in urban-grown crops, affects 12–40% of compostable residues, often exceeding regulatory thresholds (EU 86/278/EEC for Cd/Pb) (91). To ensure safe reuse, preprocessing steps such as biochar stabilization may be required (92). Additionally, integrating AI-driven waste classification and

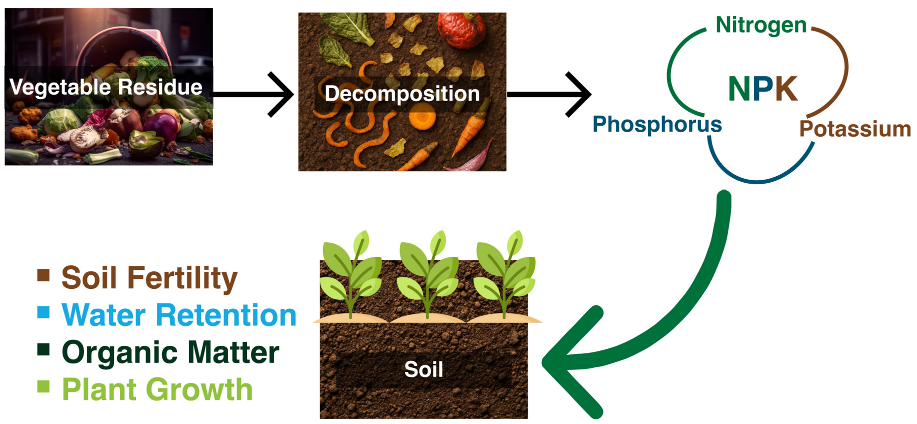


FIGURE 3
Process of vegetable residue decomposition and its impact on soil fertility and plant growth. Illustrates the breakdown of vegetable residue into nutrients (NPK) enhancing soil properties and promoting plant development.

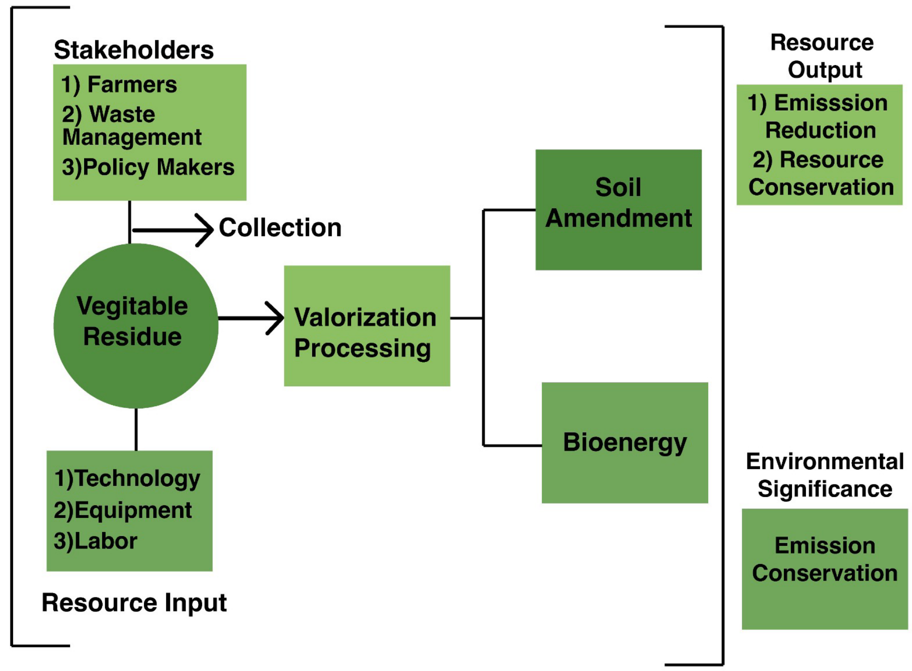


FIGURE 4
Conceptual framework of circular agriculture through valorization of vegetable residue.

blockchain-based traceability systems could optimize residue sorting and supply chain transparency (93). A systems-level approach, combining technological innovation with policy incentives, could reduce landfill dependence by 30–50%, while aligning with SDG 12.3's target to halve food waste by 2030 (see Table 3 for challenges and mitigations) (51, 94–96).

4 Challenges and research gaps

4.1 Technical constraints

The processing and management of residue materials face significant technical challenges, particularly due to high moisture content and compositional variability, which hinder efficient pre-treatment, drying, and standardization (97–99). For instance, press water (PW) from wood fuel preparation contains 60–80% moisture, requiring energy-intensive mechanical pressing and thermal drying, yet residual moisture persists even under vacuum-drying conditions (≤5% remaining at 60°C and 0.1 bar) due to strong cellulose-water interactions (100, 101). Similarly, municipal solid residue (MSR) exhibits moisture levels of 30–50%, complicating drying processes, while its heterogeneous organic–inorganic composition (e.g., 40–60% organic matter, 20–40% inert materials) impedes standardization. Industrial residues further exacerbate variability, with pH fluctuations (4.5–8.5) and elemental disparities (e.g., C/N ratios of 15–50) destabilizing co-digestion efficiency with sewage sludge by up to 30%. These constraints demand adaptive solutions, including advanced dewatering technologies (e.g., superheated steam drying, reducing energy use by 25%) and AI-driven compositional analysis, to enhance process flexibility while maintaining output quality (102–104). Addressing these gaps is critical to improving resource recovery, reducing energy burdens (current drying consumes 15–30% of total processing energy), and achieving sustainable residue management (100, 105–107).

TABLE 3 Challenges and mitigation strategies in vegetable residue valorization.

Challenge	Description	Research need	Policy recommendation
Pathogen survival	Risk during raw application	Microbial risk assessment tools	Mandatory pretreatment guidelines
Heavy metal contamination	Risk in urban compost and MSW inputs	Real-time sensors for metal detection	Set regulatory limits in compost certification
High moisture content	Reduces energy efficiency in drying or pyrolysis	Develop low-energy dewatering techniques	Fund drying innovation for SMEs
Public awareness and adoption	Limited farmer knowledge	Impact assessment studies on soil performance	Lunch agro-reuse campaigns

4.2 Economic challenges

High capital costs and uncertain returns deter investment in residue processing technologies. Small-scale pyrolysis units require \$20,000–\$50,000 upfront with payback periods exceeding five years, compared to synthetic fertilizers' immediate affordability (49). Market immaturity also plays a role where biofertilizers occupy just 1.2% of the \$190 billion synthetic fertilizer market due to farmer uncertainty and delayed nutrient release (53). Successful models, however, demonstrate viable pathways. Brazil's "ABC Program" subsidizes 60% of anaerobic digester costs for farms, while the Netherlands' "Waste-to-Farm" initiative reduces feedstock expenses by 25% through supermarket-grower partnerships (96, 97). Scaling such approaches requires targeted subsidies, circular business models, and awareness campaigns to demonstrate long-term agronomic and economic benefits (108).

4.3 Social and behavioral factors

Limited knowledge, cultural preferences for chemical fertilizers, and the perception that it will be labor-intensive are the main reasons why farmers are reluctant to embrace residue valorization (44). Despite the long-term benefits to soil health, surveys show that many small-scale farmers consider composting to be more time-consuming than synthetic fertilizers (17). Furthermore, while contributing to air pollution, conventional methods like as open-field burning continue to be used because they are convenient (99). To modify attitudes, behavioral change initiatives and examples of successful case studies must be presented (109).

4.4 Policy and regulatory gaps

The valorization of vegetable residues faces significant policy fragmentation, particularly in compost safety standards and enforcement. For instance, the European Union's stringent thresholds (EC No. 2003/2003) for heavy metals, 150 mg/kg for lead, restrict cross-border trade of organic amendments, unlike more lenient regulations in developing nations like India's 300 mg/kg limit (110). This disparity undermines global market integration for compost products. Additionally, certification systems for residue-derived fertilizers remain underdeveloped, with only 12% of low-income countries implementing quality control programs (91). Without enforced pretreatment protocols examples like thermophilic composting for pathogen reduction, untreated residues risk contaminating soils and food systems (88). Urban-rural policy disparities further intensify adoption challenges; while municipal biogas projects in China receive subsidies of approximately thirty million Chinese yuan, smallholder farmers lack equivalent financial support (111). Risks are further increased by lax enforcement since untreated leftovers could contaminate food systems (112). To address these gaps, harmonized international standards like Codex Alimentarius guidelines and incentive-based mechanisms such as California's "carbon credit for compost" program (\$50/ton for carbon sequestration) are essential to align stakeholder interests Legislators must create uniform standards and use certification programs to reward adherence (113).

4.5 Logistical issues

Collection and transportation are made more difficult by the decentralized character of vegetable residue generation, especially in rural locations (100). Rapid processing is required due to perishability, although storage facilities are frequently insufficient (114). Large-scale composting in urban settings is limited by space, and biomass aggregation is a problem for remote farms (97). These difficulties might be lessened by community-based composting centers and mobile pyrolysis units (115).

4.6 Pathogen and contaminant risks

By accumulating dangerous germs and heavy metals, vegetable residue presents serious hazards of contamination and pathogens. The necessity for better water management techniques to reduce these dangers is highlighted by studies showing that pathogens like *Salmonella Typhimurium* and *Listeria monocytogenes* can survive in hydroponic systems and contaminate lettuce throughout its growing cycle (116). Furthermore, raw vegetables may become infected by irrigation water tainted with these infections; river waters have higher concentrations of Salmonella than other sources (117). Additionally, the use of compost made from municipal solid residue in urban agriculture raises worries regarding the buildup of heavy metals in crops. greater concentrations of these metals are seen at greater compost ratios, which calls for strict monitoring to guarantee food safety (110). The significance of putting into practice efficient mitigation techniques to deal with both chemical and microbiological contaminants in vegetable production systems is generally highlighted by these findings (109, 118).

5 Innovations and future directions

5.1 Emerging AI and low-energy technologies

Current studies in machine vision-based deep learning systems like MoistNet and low-energy biodrying provide scalable answers to the main problems of vegetable residue valuation in resource-constrained environments (106). High moisture content, a paucity of shredders, and restricted access to pyrolysis units are obstacles to traditional composting and biochar production, especially for smallholders (119). In contrast, MoistNet allows for real-time, non-invasive moisture assessment through RGB or hyperspectral imaging, allowing for dynamic feedstock classification for optimal processing (120). High-moisture residues are diverted to passive solar biodrying, which reduces preprocessing energy demands by up to 40%, while low-moisture residues less than 15% can be directly pyrolyzed in flame-cap kilns

(121, 122). This approach minimizes reliance on mechanical shredders and centralized pyrolysis infrastructure, as automated moisture prediction (RMSE <2%) ensures consistent biochar yields even with heterogeneous feedstocks (122, 123). Integrating MoistNet with edge-computing devices such as Raspberry Pi, facilitates decentralized residue management, enabling smallholders to adopt precision agriculture techniques without capital-intensive equipment (124). Field trials have shown a 30–50% improvement in biochar consistency when MoistNet-guided protocols are applied, highlighting its potential for sustainable biomass valorization (125).

5.2 Biotechnological advancements

Biotechnological advancements, particularly in the fields of microbial inoculants and enzymatic pretreatment, are transforming the management of vegetable residue by enhancing decomposition efficiency and resource recovery. Engineered microbial inoculants, comprising tailored strains of bacteria and fungi, accelerate the breakdown of recalcitrant components like cellulose and lignin, reducing composting time and improving nutrient retention in the end products (126, 127).

These inoculants also suppress pathogens and enhance biogas production in anaerobic digestion systems, making them versatile tools for residue valorization. Complementing this, enzymatic pretreatment employs specific enzymes such as cellulase and ligninase to degrade complex plant structures, thereby increasing the digestibility of vegetable residue for downstream processes like biofuel production and composting (128).

Beyond traditional biotechnologies, emerging tools are revolutionizing residue valorization. AI-assisted residue sorting like hyperspectral imaging could optimize feedstock composition for microbial consortia by precisely segregating lignocellulosic fractions (129). Concurrently, CRISPR-modified *Trichoderma* strains demonstrate enhanced ligninolytic activity (up to 40% faster degradation than wild-type strains), addressing a key bottleneck in biochar production. These innovations synergize with existing microbial approaches to accelerate decomposition while reducing preprocessing energy costs (130).

The synergy between these technologies, where enzymatic pretreatment simplifies residue substrates and microbial inoculants further decompose them, offers a sustainable solution for converting low-value organic residue into high-value products like biofuels, compost, and animal feed (131). Despite challenges such as cost-effectiveness and regulatory hurdles, ongoing research in genetic engineering and synthetic biology promises to optimize these technologies, paving the way for their integration into circular economy frameworks (132).

5.3 Integrated residue management systems

Integrated Residue Management Systems (IRMS) offer a sustainable solution for managing vegetable residue by combining composting, anaerobic digestion, and biochar production to maximize resource recovery and minimize environmental impact. Vegetable residue, rich in organic matter, can be composted to produce nutrient-rich soil amendments that enhance soil health and support agricultural productivity (133, 134). Anaerobic digestion processes this residue to generate biogas, a renewable energy source, while also producing digestate that can be used as fertilizer. Additionally, converting vegetable residue into biochar through pyrolysis not only sequesters carbon but also creates a stable soil conditioner that improves water retention and nutrient availability (85).

By integrating these technologies, IRMS ensures efficient utilization of vegetable residue, reduces greenhouse gas emissions, and supports circular economy principles. Studies highlight that such systems can significantly enhance residue valorization and contribute to climate change mitigation (115).

5.4 Circular agriculture integration in vegetable residue valorization

The integration of design principles and closed-loop systems in vegetable valorization emphasizes sustainable techniques that improve resource efficiency and reduce residue (128). Advanced extraction techniques, such as subcritical and supercritical fluid technologies, allow the recovery of bioactive chemicals from vegetable residue, contributing to a circular agriculture by transforming residue into beneficial products for the food and pharmaceutical industries (135). In addition, bioponic systems use organic residue streams as nutrient sources, promoting local nutrient cycling and enhancing plant development while lowering dependency on conventional fertilizers (134). Composting in controlled environment agriculture (CEA) reinforces this closed-loop method by turning biowaste into nutrients for crop production, thus reducing environmental concerns (128).

The EU Waste Framework Directive, as well as subsidies for residue-to-resource initiatives, play critical roles in supporting sustainable practices in the bio-based economy. These policies stimulate the valorization of agricultural residues and food waste, facilitating the transition to a circular agriculture by including composting and biowaste management into urban farm systems (96, 134). However, scalability issues persist, notably with decentralized composting hubs and the certification of biochar for carbon credits, which require solid regulatory frameworks and stakeholder participation to enable effective implementation (136, 137). Integrating these approaches not only improves resource recovery but also tackles environmental problems, therefore contributing to a carbon-negative cycle in agricultural systems (138).

Metrics for analyzing circular agriculture performance in vegetable valorization include parameters such as resource efficiency, carbon footprint reduction, and economic feasibility. Nutrient recovery rates can be used to quantify resource efficiency. According to studies, only 9.6% of materials processed in the EU were secondary materials, emphasizing the need for enhanced recycling processes (139). Carbon footprint reductions are evident in food-residue reduction initiatives, where turning surplus food into processed products resulted in net revenue and variable CO_2 savings, highlighting the potential for sustainable practices (140). Circular production models, such as those used in olive oil manufacturing, have been shown to save costs and improve sustainability by reducing the use of virgin materials and residue (141). Furthermore, urban regeneration programs that prioritize recycling can significantly decrease greenhouse gas emissions, adding to the economic and environmental benefits of circular agriculture principles (142).

6 Conclusion

The valorization of vegetable residues through soil replenishment offers a scientifically validated pathway to address global challenges in residue management and agricultural sustainability. This review demonstrates that composting, vermicomposting, anaerobic digestion, and biochar production effectively transform residues into resources, enhancing soil fertility (e.g., SOC increase by 15–30%, CEC improvement by 20–40%), mitigating greenhouse gas emissions (e.g., 30–80% reduction in landfill methane), and reducing reliance on synthetic fertilizers. The biochemical richness of vegetable residues cellulose, hemicellulose, and essential nutrients supports microbial diversity and nutrient cycling, underpinning circular agriculture principles.

Despite these benefits, challenges persist, including pathogen risks (e.g., *Salmonella* survival in untreated residues), heavy metal contamination (e.g., Pb/Cd accumulation), and economic barriers (e.g., high pyrolysis unit costs). Emerging innovations AI-driven moisture sensors (MoistNet, RMSE <2%), CRISPR-enhanced microbial consortia (40% faster lignin degradation), and integrated systems (compost-biochar synergies) show promise in overcoming these limitations. Policy frameworks must prioritize standardized compost safety regulations (e.g., harmonizing EU/India heavy metal thresholds) and incentivize adoption through subsidies (e.g., Brazil's ABC Program).

Future research should focus on field-scale validation of integrated technologies under diverse pedoclimatic condition, lifecycle assessments to quantify net carbon sequestration and energy efficiency and socioeconomic models to accelerate farmer uptake. By bridging these gaps, vegetable residue valorization can transition from a niche practice to a cornerstone of sustainable agriculture, aligning with SDGs 2 (Zero Hunger) by improving soil productivity and 13 (Climate Action) through carbon sequestration. The imperative is clear: interdisciplinary collaboration and policy action are essential to scale these solutions and secure resilient food systems for a growing population.

Author contributions

KQ: Writing – review & editing, Writing – original draft. RA-A: Writing – review & editing, Visualization, Conceptualization. FX: Conceptualization, Writing – review & editing. SX: Writing – review & editing. LM: Writing – review & editing. WD: Writing – review & editing. WJ: Validation, Conceptualization, Writing – review & editing, Supervision, Resources. GM: Funding acquisition, Validation, Conceptualization, Writing – review & editing, Supervision, Formal Analysis, Investigation, Resources. MX: Writing – review & editing.

Funding

The author(s) declare that financial support was received for the research and/or publication of this article. This work was supported by the China Agriculture Research System of MOF and MARA (CARS-23-B12).

Conflict of interest

The remaining authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

Generative AI statement

The author(s) declare that no Generative AI was used in the creation of this manuscript.

Publisher's note

References

1. Cederberg C, Sonesson U. *Global food losses and food waste: extent, causes and prevention; study conducted for the International Congress Save Food! at Interpack 2011*. Gustavsson J, editor. Düsseldorf, Germany: Food and Agriculture Organization of the United Nations (2011). p. 29. Rome.

2. Chiaraluce G, Bentivoglio D, Finco A. Circular economy for a sustainable agri-food supply chain: A review for current trends and future pathways. *Sustainability*. (2021) 13:9294. doi: 10.3390/su13169294

3. Rodrigues JPB, Liberal Â, Petropoulos SA, Ferreira ICFR, Oliveira MBPP, Fernandes Â, et al. Agri-food surplus, waste and loss as sustainable biobased ingredients: A review. *Molecules*. (2022) 27:5200. doi: 10.3390/molecules27165200

4. Pérez-Marroquín XA, Estrada-Fernández AG, García-Ceja A, Aguirre-Álvarez G, León-López A. Agro-food waste as an ingredient in functional beverage processing: sources, functionality, market and regulation. *Foods*. (2023) 12:1583. doi: 10.3390/foods12081583

5. Srivastava N, Malik MA eds. *Food Waste to Green Fuel: Trend & Development*. Singapore: Springer Nature Singapore (2022). doi: 10.1007/978-981-19-0813-2

6. Dede C, Ozer H, Dede OH, Celebi A, Ozdemir S. Recycling nutrient-rich municipal wastes into ready-to-use potting soil: an approach for the sustainable resource circularity with inorganic porous materials. *Horticulturae*. (2023) 9:203. doi: 10.3390/horticulturae9020203

7. FAO, IFAD, UNICEF, WFP and WHO. "In Brief to The State of Food Security and Nutrition in the World 2022." In: *Repurposing food and agricultural policies to make healthy diets more affordable*. Rome: FAO. (2022). doi: 10.4060/cc0640en

8. Esparza I, Jiménez-Moreno N, Bimbela F, Ancín-Azpilicueta C, Gandía LM. Fruit and vegetable waste management: Conventional and emerging approaches. *J Environ Manage*. (2020) 265:110510. doi: 10.1016/j.jenvman.2020.110510

9. Homeshvari, Hrahsel L, Kanaka S, Zeeshan M, IM K, Shakeel A, et al. Revolutionizing fruit agriculture of cutting edge farming technologies to growing food demands globally. *IJECC*. (2024) 14:681–7. doi: 10.9734/ijecc/2024/v14i13883

10. Pereira MMA, Moraes LC, Mogollón MCT, Borja CJF, Duarte M, Buttrós VHT, et al. Cultivating biodiversity to harvest sustainability: vermicomposting and inoculation of microorganisms for soil preservation and resilience. *Agronomy*. (2022) 13:103. doi: 10.3390/agronomy13010103

11. Butnaru E, Brebu M. The thermochemical conversion of forestry residues from silver fir (Abies alba mill.) by torrefaction and pyrolysis. *Energies*. (2022) 15:3483. doi: 10.3390/en15103483

12. Max K, Shannon K, Jenny S, Amanda S. Quantifying Methane Emissions from Landfilled Food Waste. United States of America: US Environmental Protection Agency Office of Research and Development EPA-600-R-23-064 (2023). Available online at: https://www.epa.gov/ghgreporting/subpart-hh-information-sheet (Accessed July 9, 2025).

13. Luo L, Wu X, Li Z, Zhou Y, Chen T, Fan M, et al. Synthesis of activated carbon from biowaste of fir bark for methylene blue removal. *R Soc Open Sci*. (2019) 6:190523. doi: 10.1098/rsos.190523

14. Li L, Tong L, Lv Y. Influence of bio-fertilizer type and amount jointly on microbial community composition, crop production and soil health. *Agronomy*. (2023) 13:1775. doi: 10.3390/agronomy13071775

15. Dimou MD, Monokrousos N, Katapodis P, Diamantopoulou PA, Argyropoulou MD, Papatheodorou EM. Use of microbially treated olive mill wastewaters as soil organic amendments; their short-term effects on the soil nematode community. *Diversity*. (2023) 15:497. doi: 10.3390/d15040497

16. Liu X, Shi Y, Kong L, Tong L, Cao H, Zhou H, et al. Long-term application of bio-compost increased soil microbial community diversity and altered its composition and network. *Microorganisms*. (2022) 10:462. doi: 10.3390/microorganisms10020462

17. Assirelli A, Fornasier F, Caputo F, Manici LM. Locally available compost application in organic farms: 2-year effect on biological soil properties. *Renewable Agric Food Syst*. (2023) 38:1–9. doi: 10.1017/S1742170523000078

18. Aguilar-Paredes A, Valdés G, Araneda N, Valdebenito E, Hansen F, Nuti M. Microbial community in the composting process and its positive impact on the soil biota in sustainable agriculture. *Agronomy*. (2023) 13:542. doi: 10.3390/agronomy13020542

19. Ronga D, Mantovi P, Pacchioli MT, Pulvirenti A, Bigi F, Allesina G, et al. Combined effects of dewatering, composting and pelleting to valorize and delocalize livestock manure, improving agricultural sustainability. *Agronomy*. (2020) 10:661. doi: 10.3390/agronomy10050661

20. Gerke J. The central role of soil organic matter in soil fertility and carbon storage. *Soil Syst*. (2022) 6:33. doi: 10.3390/soilsystems6020033

21. Nadarajah K, Abdul Rahman NSN. The microbial connection to sustainable agriculture. *Plants*. (2023) 12:2307. doi: 10.3390/plants12122307

22. Siedt M, Teggers E-M, Linnemann V, Schäffer A, Van Dongen JT. Microbial degradation of plant residues rapidly causes long-lasting hypoxia in soil upon irrigation and affects leaching of nitrogen and metals. *Soil Syst*. (2023) 7:62. doi: 10.3390/soilsystems7020062

23. Chen Y, Xu M, Yang L, Jing H, Mao W, Liu J, et al. A critical review of biochar application for the remediation of greenhouse gas emissions and nutrient loss in rice paddies: characteristics, mechanisms, and future recommendations. *Agronomy*. (2023) 13:893. doi: 10.3390/agronomy13030893

24. Abbas A, Duan J, Abdoulaye AH, Fu Y, Lin Y, Xie J, et al. Deciphering bacterial community of the fallow and paddy soil focusing on possible biocontrol agents. *Agronomy*. (2022) 12:431. doi: 10.3390/agronomy12020431

25. Zhang W-G, Zhang M-S, Li W. The antibiotic resistance genes contamination of strawberries with the long-term use of raw, aerobic composting, and anaerobic composting livestock manure: A comparative study. *Front Environ Sci*. (2022) 10:902321. doi: 10.3389/fenvs.2022.902321

26. Zainudin MHM, Zulkarnain A, Azmi AS, Muniandy S, Sakai K, Shirai Y, et al. Enhancement of agro-industrial waste composting process via the microbial inoculation: A brief review. *Agronomy*. (2022) 12:198. doi: 10.3390/agronomy12010198

27. Finore I, Feola A, Russo L, Cattaneo A, Di Donato P, Nicolaus B, et al. Thermophilic bacteria and their thermozymes in composting processes: a review. *Chem Biol Technol Agric*. (2023) 10:7. doi: 10.1186/s40538-023-00381-z

28. He X, Cong R, Gao W, Duan X, Gao Y, Li H, et al. Optimization of composting methods for efficient use of cassava waste, using microbial degradation. *Environ Sci Pollut Res*. (2023) 30:51288–302. doi: 10.1007/s11356-023-25818-8

29. Wu X, Ren L, Luo L, Zhang J, Zhang L, Huang H. Bacterial and fungal community dynamics and shaping factors during agricultural waste composting with zeolite and biochar addition. *Sustainability*. (2020) 12:7082. doi: 10.3390/su12177082

30. Yatoo AM, Bhat SA, MdN A, ZA B, Zaheen Z. Production of nutrient-enriched vermicompost from aquatic macrophytes supplemented with kitchen waste: assessment of nutrient changes, phytotoxicity, and earthworm biodynamics. *Agronomy*. (2022) 12:1303. doi: 10.3390/agronomy12061303

31. Ajibade S, Mupambwa HA, Manyevere A, Mnkeni PNS. Vermicompost Amended with Rock Phosphate as a Climate Smart Technology for Production of Organic Swiss Chard (Beta vulgaris subsp. vulgaris). *Front Sustain Food Syst*. (2022) 6:757792. doi: 10.3389/fsufs.2022.757792

32. Wang H, Chen S, Gu J, Liu Y, Yang G, Su W, et al. Biolysed sludge composting for nitrogen conservation and humification improvements and mechanisms. *Sustainability*. (2023) 15:10119. doi: 10.3390/su151310119

33. Oyege I, Balaji Bhaskar MS. Effects of vermicompost on soil and plant health and promoting sustainable agriculture. *Soil Syst*. (2023) 7:101. doi: 10.3390/soilsystems7040101

34. Blouin M, Barrere J, Meyer N, Lartigue S, Barot S, Mathieu J. Vermicompost significantly affects plant growth. A meta-analysis. *Agron Sustain Dev*. (2019) 39. doi: 10.1007/s13593-019-0579-x

35. Huang C, Li R, Tang W, Zheng Y, Meng X. Improve enzymatic hydrolysis of lignocellulosic biomass by modifying lignin structure via sulfite pretreatment and using lignin blockers. *Fermentation*. (2022) 8:558. doi: 10.3390/fermentation8100558

36. Dawar K, Khan A, Mian IA, Khan B, Ali S, Ahmad S, et al. Maize productivity and soil nutrients variations by the application of vermicompost and biochar. *PLoS ONE*. (2022) 17:5. doi: 10.1371/journal.pone.0267483

37. Xu D, Yu X, Chen J, Li X, Chen J, Li J. Effects of compost as a soil amendment on bacterial community diversity in saline–alkali soil. *Front Microbiol*. (2023) 14:1253415. doi: 10.3389/fmicb.2023.1253415

38. Palaniveloo K, Amran MA, Norhashim NA, Mohamad-Fauzi N, Peng-Hui F, Hui-Wen L, et al. Food waste composting and microbial community structure profiling. *Processes*. (2020) 8:723. doi: 10.3390/pr8060723

39. Zainal A, Harun R, Idrus S. Performance monitoring of anaerobic digestion at various organic loading rates of commercial Malaysian food waste. *Front Bioeng Biotechnol*. (2022) 10:775676. doi: 10.3389/fbioe.2022.775676

40. Ali AM, Zahangir A, Abdoul-Latif FM, Jami MS, Mohamed J, Ainane T. Hydrolysis of food waste with immobilized biofilm as a pretreatment method for the enhancement of biogas production. *Sustainability*. (2023) 15. doi: 10.3390/su15043316

41. Chukwuma OB, Rafatullah M, Tajarudin HA, Ismail N. Lignocellulolytic enzymes in biotechnological and industrial processes: A review. *Sustainability*. (2020) 12:7282. doi: 10.3390/su12187282

42. Ma H, Liu H, Zhang L, Yang M, Fu B, Liu H. Novel insight into the relationship between organic substrate composition and volatile fatty acids distribution in acidogenic co-fermentation. *Biotechnol Biofuels*. (2017) 10:137. doi: 10.1186/s13068-017-0821-1

43. Lukitawesa, Patinvoh RJ, Millati R, Sárvári-Horváth I, Taherzadeh MJ. Factors influencing volatile fatty acids production from food wastes via anaerobic digestion. *Bioengineered*. (2020) 11:39–52. doi: 10.1080/21655979.2019.1703544

44. Khangura R, Ferris D, Wagg C, Bowyer J. Regenerative agriculture—A literature review on the practices and mechanisms used to improve soil health. *Sustainability*. (2023) 15:2338. doi: 10.3390/su15032338

45. Lee H, Bae J, Jin S, Kang S, Cho B-K. Engineering acetogenic bacteria for efficient one-carbon utilization. *Front Microbiol*. (2022) 13:865168. doi: 10.3389/fmicb.2022.865168

46. Guarda EC, Costa E, Gil C, Amorim CL, Galinha CF, Duque AF, et al. Acidogenic fermentation of brewers' Spent grain monitored through two-dimensional fluorescence spectroscopy. *ACS Sustain Chem Eng*. (2023) 11:7398–406. doi: 10.1021/acssuschemeng.3c00316

47. Mu L, Wang Y, Xu F, Li J, Tao J, Sun Y, et al. Emerging strategies for enhancing propionate conversion in anaerobic digestion: A review. *Molecules*. (2023) 28:3883. doi: 10.3390/molecules28093883

48. Oliva A, Papirio S, Esposito G, Lens PNL. Impact of chemical and physical pretreatment on methane potential of peanut shells. *Energies*. (2023) 16:4698. doi: 10.3390/en16124698

49. Jamal M. Mathematical modelling of biogas production in a controlled landfill: characterization, valorization study and energy potential. *Sustainability*. (2022) 14:15490. doi: 10.3390/su142315490

50. Volmer JG, Soo RM, Evans PN, Hoedt EC, Astorga Alsina AL, Woodcroft BJ, et al. Isolation and characterisation of novel Methanocorpusculum species indicates the genus is ancestrally host-associated. *BMC Biol*. (2023) 21:59. doi: 10.1186/s12915-023-01524-2

51. Atchike DW, Irfan M, Ahmad M, Rehman MA. Waste-to-renewable energy transition: biogas generation for sustainable development. *Front Environ Sci*. (2022) 10:840588. doi: 10.3389/fenvs.2022.840588

52. Carvalho FSD, Reis LCBDS, Lacava PT, Araújo FHMD, Carvalho JAD Jr. Substitution of natural gas by biomethane: operational aspects in industrial equipment. *Energies*. (2023) 16:839. doi: 10.3390/en16020839

53. Elkhlifi Z, Iftikhar J, Sarraf M, Ali B, Saleem MH, Ibranshahib I, et al. Potential role of biochar on capturing soil nutrients, carbon sequestration and managing environmental challenges: A review. *Sustainability*. (2023) 15:2527. doi: 10.3390/su15032527

54. Nair RR, Kißling PA, Marchanka A, Lecinski J, Turcios AE, Shamsuyeva M, et al. Biochar synthesis from mineral and ash-rich waste biomass, part 2: characterization of biochar and co-pyrolysis mechanism for carbon sequestration. *Sustain Environ Res*. (2023) 33:14. doi: 10.1186/s42834-023-00176-9

55. Sun J, Lu X, Chen G, Luo N, Zhang Q, Li X. Biochar promotes soil aggregate stability and associated organic carbon sequestration and regulates microbial community structures in Mollisols from northeast China. *SOIL*. (2023) 9:261–75. doi: 10.5194/soil-9-261-2023

56. Cárdenas-Aguiar E, Méndez A, Paz-Ferreiro J, Sohi SP, Gascó G. Thermal analysis of aged chars obtained by pyrolysis and hydrothermal carbonisation of manure wastes. *J Therm Anal Calorim*. (2023) 148:7395–401. doi: 10.1007/s10973-023-12199-w

57. Harrison BP, Chopra E, Ryals R, Campbell JE. Quantifying the farmland application of compost to help meet california's organic waste diversion law. *Environ Sci Technol*. (2020) 54:4545–53. doi: 10.1021/acs.est.9b05377

58. Larkin RP. Long-term effects of compost amendments and brassica green manures in potato cropping systems on soil and crop health and productivity. *Agronomy*. (2022) 12:2804. doi: 10.3390/agronomy12112804

59. Ducasse V, Capowiez Y, Peigné J. Vermicomposting of municipal solid waste as a possible lever for the development of sustainable agriculture. *A review. Agron Sustain Dev*. (2022) 42:89. doi: 10.1007/s13593-022-00819-y

60. Schröder C, Häfner F, Larsen OC, Krause A. Urban organic waste for urban farming: growing lettuce using vermicompost and thermophilic compost. *Agronomy*. (2021) 11:1175. doi: 10.3390/agronomy11061175

61. Scott A, Blanchard R. The role of anaerobic digestion in reducing dairy farm greenhouse gas emissions. *Sustainability*. (2021) 13:2612. doi: 10.3390/su13052612

62. Jindo K, Sonoki T. Comparative assessment of biochar stability using multiple indicators. *Agronomy*. (2019) 9:254. doi: 10.3390/agronomy9050254

63. Layek J, Narzari R, Hazarika S, Das A, Rangappa K, Devi S, et al. Prospects of biochar for sustainable agriculture and carbon sequestration: an overview for eastern himalayas. *Sustainability*. (2022) 14:6684. doi: 10.3390/su14116684

64. Yang Y. Improvement of rural soil properties and states by biomass carbon under the concept of sustainability: A research progress. *Front Chem*. (2022) 10:1078170. doi: 10.3389/fchem.2022.1078170

65. Elrys AS, Elnahal AS, Abdo AI, Desoky E-SM, Selem E, Rady MM. Traditional, modern, and molecular strategies for improving the efficiency of nitrogen use in crops for sustainable agriculture: a fresh look at an old issue. *J Soil Sci Plant Nutr*. (2022) 22:3130–56. doi: 10.1007/s42729-022-00873-1

66. Osman AI, Fawzy S, Farghali M, El-Azazy M, Elgarahy AM, Fahim RA, et al. Biochar for agronomy, animal farming, anaerobic digestion, composting, water treatment, soil remediation, construction, energy storage, and carbon sequestration: a review. *Environ Chem Lett*. (2022) 20:2385–485. doi: 10.1007/s10311-022-01424-x

67. Bong CPC, Lim LY, Lee CT, Ong PY, Fan YV, Klemeš JJ. Integrating compost and biochar towards sustainable soil management. *Chem Eng Trans*. (2021) 86:1345–50. doi: 10.3303/CET2186225

68. Bhattacharyya SS, Furtak K. Soil–plant–microbe interactions determine soil biological fertility by altering rhizospheric nutrient cycling and biocrust formation. *Sustainability*. (2023) 15:625. doi: 10.3390/su15010625

69. Pane C, Sorrentino R, Scotti R, Molisso M, Di Matteo A, Celano G, et al. Alpha and beta-diversity of microbial communities associated to plant disease suppressive functions of on-farm green composts. *Agriculture*. (2020) 10:113. doi: 10.3390/agriculture10040113

70. Yadav GK, Dadhich SK, Yadav RK, Kumar R, Dobaria J, Paray BA, et al. Impact of biomass recycling and fertilization on soil microbiological characteristics and wheat productivity in semi-arid environment. *Agronomy*. (2023) 13:1054. doi: 10.3390/agronomy13041054

71. Khaliq A, Perveen S, Alamer KH, Zia Ul Haq M, Rafique Z, Alsudays IM, et al. Arbuscular mycorrhizal fungi symbiosis to enhance plant–soil interaction. *Sustainability*. (2022) 14:7840. doi: 10.3390/su14137840

72. Ren W, Guo Y, Han X, Sun Y, Li Q, Wu B, et al. Indigenous microorganisms offset arbuscular mycorrhizal fungi-induced plant growth and nutrient acquisition through negatively modulating the genes of phosphorus transport and nitrogen assimilation. *Front Plant Sci*. (2022) 13:880181. doi: 10.3389/fpls.2022.880181

73. Rai AK, Basak N, Dixit AK, Rai SK, Das SK, Singh JB, et al. Changes in soil microbial biomass and organic C pools improve the sustainability of perennial grass and legume system under organic nutrient management. *Front Microbiol*. (2023) 14:1173986. doi: 10.3389/fmicb.2023.1173986

74. Poeplau C, Don A. A simple soil organic carbon level metric beyond the organic carbon-to-clay ratio. *Soil Use Manage*. (2023) 39:1057–67. doi: 10.1111/sum.12921

75. Anjali, Jena A, Bamola A, Mishra S, Jain I, Pathak N, et al. State-of-the-art non-destructive approaches for maturity index determination in fruits and vegetables: principles, applications, and future directions. *Food Prod Process Nutr*. (2024) 6:56. doi: 10.1186/s43014-023-00205-5

76. Hossain M, Islam SMS, Hasan M. Changes in soil properties with combined use of probiotic cultures and organic farming practices in degraded soils of Bangladesh. *Sustainability*. (2023) 15:4430. doi: 10.3390/su15054430

77. Pérez T, Vergara SE, Silver WL. Assessing the climate change mitigation potential from food waste composting. *Sci Rep*. (2023) 13. doi: 10.1038/s41598-023-34174-z

78. Li P, Li W, Sun M, Xu X, Zhang B, Sun Y. Evaluation of biochemical methane potential and kinetics on the anaerobic digestion of vegetable crop residues. *Energies*. (2018) 12:26. doi: 10.3390/en12010026

79. Griscom BW, Adams J, Ellis PW, Houghton RA, Lomax G, Miteva DA, et al. Natural climate solutions. *Proc Natl Acad Sci USA*. (2017) 114:11645–50. doi: 10.1073/pnas.1710465114

80. Wunderlich SM. Protecting the environment by reducing food loss and waste across the food supply chain. *WIT Press*. (2020), 245:31–9. doi: 10.2495/EID200041

81. Khaksar G, Sirijan M, Suntichaikamolkul N, Sirikantaramas S. Metabolomics for agricultural waste valorization: shifting toward a sustainable bioeconomy. *Front Plant Sci*. (2022) 13:938480. doi: 10.3389/fpls.2022.938480

82. Almeida PV, Gando-Ferreira LM, Quina MJ. Biorefinery perspective for industrial potato peel management: technology readiness level and economic assessment. *J Environ Chem Eng*. (2023) 11:110049. doi: 10.1016/j.jece.2023.110049

83. Intergovernmental Panel on Climate Change. *Climate change 2014: mitigation of climate change: Working Group III contribution to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change*. Edenhofer O, editor. New York, NY: Cambridge University Press (2014). p. 1435.

84. Lemes AC, Egea MB, Oliveira Filho JGD, Gautério GV, Ribeiro BD, Coelho MAZ. Biological approaches for extraction of bioactive compounds from agro-industrial by-products: A review. *Front Bioeng Biotechnol*. (2022) 9:802543. doi: 10.3389/fbioe.2021.802543

85. Casini D, Barsali T, Rizzo AM, Chiaramonti D. Production and characterization of co-composted biochar and digestate from biomass anaerobic digestion. *Biomass Conv Bioref*. (2021) 11:2271–9. doi: 10.1007/s13399-019-00482-6

86. Vejvodová K, Ash C, Dajčl J, Tejnecký V, Johanis H, Spasić M, et al. Assessment of potential exposure to As, Cd, Pb and Zn in vegetable garden soils and vegetables in a mining region. *Sci Rep*. (2022) 12:13495. doi: 10.1038/s41598-022-17461-z

87. Shen G, Ru X, Gu Y, Liu W, Wang K, Li B, et al. Pollution characteristics, spatial distribution, and evaluation of heavy metal(loid)s in farmland soils in a typical mountainous hilly area in China. *Foods*. (2023) 12:681. doi: 10.3390/foods12030681

88. Ullah N, Ur Rehman M, Ahmad B, Ali I, Younas M, Aslam MS, et al. Assessment of heavy metals accumulation in agricultural soil, vegetables and associated health risks. *PloS One*. (2022) 17:e0267719. doi: 10.1371/journal.pone.0267719

89. Bora FD, Bunea A, Pop SR, Baniţă SI, Duşa DŞ, Chira A, et al. Quantification and reduction in heavy metal residues in some fruits and vegetables: A case study galaţi county, Romania. *Horticulturae*. (2022) 8:1034. doi: 10.3390/horticulturae8111034

90. Varkolu M, Gundekari S, Omvesh, Palla VCS, Kumar P, Bhattacharjee S, et al. Recent advances in biochar production, characterization, and environmental applications. *Catalysts*. (2025) 15:243. doi: 10.3390/catal15030243

91. Lopes C, Herva M, Franco-Uría A, Roca E. Inventory of heavy metal content in organic waste applied as fertilizer in agriculture: evaluating the risk of transfer into the food chain. *Environ Sci pollut Res*. (2011) 18:918–39. doi: 10.1007/s11356-011-0444-1

92. Bolan N, Kunhikrishnan A, Thangarajan R, Kumpiene J, Park J, Makino T, et al. Remediation of heavy metal(loid)s contaminated soils – To mobilize or to immobilize? *J Hazardous Materials*. (2014) 266:141–66. doi: 10.1016/j.jhazmat.2013.12.018

93. Onyeaka H, Tamasiga P, Nwauzoma UM, Miri T, Juliet UC, Nwaiwu O, et al. Using artificial intelligence to tackle food waste and enhance the circular economy: maximising resource efficiency and minimising environmental impact: A review. *Sustainability*. (2023) 15:10482. doi: 10.3390/su151310482

94. Paritosh K, Kushwaha SK, Yadav M, Pareek N, Chawade A, Vivekanand V. Food waste to energy: an overview of sustainable approaches for food waste management and nutrient recycling. *BioMed Res Int*. (2017) 2017:1–19. doi: 10.1155/2017/2370927

95. Zhang J, Dolfing J, Liu W, Chen R, Zhang J, Lin X, et al. Beyond the snapshot: identification of the timeless, enduring indicator microbiome informing soil fertility and crop production in alkaline soils. *Environ Microbiome*. (2022) 17:25. doi: 10.1186/s40793-022-00420-6

96. Alonso-Muñoz S, García-Muiña FE, Medina-Salgado M-S, González-Sánchez R. Towards circular economy practices in food waste management: a retrospective overview and a research agenda. *BFJ*. (2022) 124:478–500. doi: 10.1108/BFJ-01-2022-0072

97. Li CH, Lee TT, Lau SSY. Enhancement of municipal solid waste management in hong kong through innovative solutions: A review. *Sustainability*. (2023) 15:3310. doi: 10.3390/su15043310

98. Watabe S, Lohman HAC, Li Y, Morgan VL, Rowles LS, Stephen T, et al. Advancing the economic and environmental sustainability of the NEWgenerator nonsewered sanitation system. *ACS Environ Au*. (2023) 3:209–22. doi: 10.1021/acsenvironau.3c00001

99. Yang Y, Liew RK, Tamothran AM, Foong SY, Yek PNY, Chia PW, et al. Gasification of refuse-derived fuel from municipal solid waste for energy production: a review. *Environ Chem Lett*. (2021) 19:2127–40. doi: 10.1007/s10311-020-01177-5

100. Sailer G, Empl F, Kuptz D, Silberhorn M, Ludewig D, Lesche S, et al. Characteristics and anaerobic co-digestion of press water from wood fuel preparation and digested sewage sludge. *Fermentation*. (2022) 8:37. doi: 10.3390/fermentation8010037

101. Sapci-Ayas Z. Investigation of direct applicability of modified agricultural waste for contaminant removal from real textile wastewater. *Water*. (2021) 13:1354. doi: 10.3390/w13101354

102. Agrawal K, Goktas P, Holtkemper M, Beecks C, Kumar N. AI-driven transformation in food manufacturing: a pathway to sustainable efficiency and quality assurance. *Front Nutr*. (2025) 12:1553942. doi: 10.3389/fnut.2025.1553942

103. Firoozi AA, Firoozi AA, Oyejobi DO, Avudaiappan S, Flores ES. Emerging trends in sustainable building materials: Technological innovations, enhanced performance, and future directions. *Results Eng*. (2024) 24:103521. doi: 10.1016/j.rineng.2024.103521

104. Skwarek P, Karwowska M. Fruit and vegetable processing by-products as functional meat product ingredients -a chance to improve the nutritional value. *LWT*. (2023) 189:115442. doi: 10.1016/j.lwt.2023.115442

105. Altgen M, Fröba M, Gurr J, Krause A, Ohlmeyer M, Sazama U, et al. Limits in reaching the anhydrous state of wood and cellulose. *Cellulose*. (2023) 30:6247–57. doi: 10.1007/s10570-023-05293-7

106. Pilnáček V, Benešová L, Cajthaml T, Inemannová P. Comparison of temperature and oxygen concentration driven aeration methods for biodrying of municipal solid waste. *Eur J Environ Sci*. (2021) 11:38–45. doi: 10.14712/23361964.2021.5

107. Kolya H, Kang C-W. Bio-based polymeric flocculants and adsorbents for wastewater treatment. *Sustainability*. (2023) 15:9844. doi: 10.3390/su15129844

108. Paramesh V, Mohan Kumar R, Rajanna GA, Gowda S, Nath AJ, Madival Y, et al. Integrated nutrient management for improving crop yields, soil properties, and reducing greenhouse gas emissions. *Front Sustain Food Syst*. (2023) 7:1173258. doi: 10.3389/fsufs.2023.1173258

109. Pandey M, Tirkey A, Tiwari A, Lee S, Dubey R, Kim K, et al. The environmental significance of contaminants of concern in the soil–vegetable interface: sources, accumulation, health risks, and mitigation through biochar. *Sustainability*. (2022) 14:14539. doi: 10.3390/su142114539

110. Bhardwaj P, Sharma RK, Chauhan A, Ranjan A, Rajput VD, Minkina T, et al. Assessment of heavy metal distribution and health risk of vegetable crops grown on soils amended with municipal solid waste compost for sustainable urban agriculture. *Water*. (2023) 15:228. doi: 10.3390/w15020228

111. Zheng L, Cheng S, Han Y, Wang M, Xiang Y, Guo J, et al. Bio-natural gas industry in China: Current status and development. *Renewable Sustain Energy Rev*. (2020) 128:109925. doi: 10.1016/j.rser.2020.109925

112. Nenciu F, Stanciulescu I, Vlad H, Gabur A, Turcu OL, Apostol T, et al. Decentralized processing performance of fruit and vegetable waste discarded from retail, using an automated thermophilic composting technology. *Sustainability*. (2022) 14:2835. doi: 10.3390/su14052835

113. Pavinato PS, Sánchez-Rodríguez AR, Tiecher T. Editorial: sustainable phosphorus use in agriculture. *Front Agron*. (2022) 4:899924. doi: 10.3389/fagro.2022.899924

114. Srivastava RR, Rajak DK, Ilyas S, Kim H, Pathak P. Challenges, regulations, and case studies on sustainable management of industrial waste. *Minerals*. (2022) 13:51. doi: 10.3390/min13010051

115. Rex P, Mohammed Ismail K, Meenakshisundaram N, Barmavatu P, Sai Bharadwaj A. Agricultural biomass waste to biochar: A review on biochar applications using machine learning approach and circular economy. *ChemEngineering*. (2023) 7:50. doi: 10.3390/chemengineering7030050

116. Ilic S, Moodispaw MR, Madden LV, Lewis Ivey ML. Lettuce contamination and survival of salmonella typhimurium and listeria monocytogenes in hydroponic nutrient film technique systems. *Foods*. (2022) 11:3508. doi: 10.3390/foods11213508

117. Sharma M, Handy ET, East CL, Kim S, Jiang C, Callahan MT, et al. Prevalence of Salmonella and Listeria monocytogenes in non-traditional irrigation waters in the Mid-Atlantic United States is affected by water type, season, and recovery method. *PloS One*. (2020) 15:e0229365. doi: 10.1371/journal.pone.0229365

118. Weller DL, Saylor L, Turkon P. Total coliform and generic E. coli levels, and salmonella presence in eight experimental aquaponics and hydroponics systems: A brief report highlighting exploratory data. *Horticulturae*. (2020) 6:42. doi: 10.3390/horticulturae6030042

119. Khawkomol S, Neamchan R, Thongsamer T, Vinitnantharat S, Panpradit B, Sohsalam P, et al. Potential of biochar derived from agricultural residues for sustainable management. *Sustainability*. (2021) 13:8147. doi: 10.3390/su13158147

120. Reddy AP, Allgaier M, Singer SW, Hazen TC, Simmons BA, Hugenholtz P, et al. Bioenergy feedstock-specific enrichment of microbial populations during high-solids thermophilic deconstruction. *Biotech Bioengineering*. (2011) 108:2088–98. doi: 10.1002/bit.23176

121. Taghinezhad E, Szumny A, Figiel A. The application of hyperspectral imaging technologies for the prediction and measurement of the moisture content of various agricultural crops during the drying process. *Molecules*. (2023) 28:2930. doi: 10.3390/molecules28072930

122. Leng L, Yang L, Lei X, Zhang W, Ai Z, Yang Z, et al. Machine learning predicting and engineering the yield, N content, and specific surface area of biochar derived from pyrolysis of biomass. *Biochar*. (2022) 4:63. doi: 10.1007/s42773-022-00183-w

123. Nepal J, Ahmad W, Munsif F, Khan A, Zou Z. Advances and prospects of biochar in improving soil fertility, biochemical quality, and environmental applications. *Front Environ Sci*. (2023) 11:1114752. doi: 10.3389/fenvs.2023.1114752

124. Ferrández-Pastor FJ, García-Chamizo JM, Nieto-Hidalgo M, Mora-Martínez J. Precision agriculture design method using a distributed computing architecture on internet of things context. *Sensors*. (2018) 18:1731. doi: 10.3390/s18061731

125. Bayih AZ, Morales J, Assabie Y, De By RA. Utilization of internet of things and wireless sensor networks for sustainable smallholder agriculture. *Sensors*. (2022) 22:3273. doi: 10.3390/s22093273

126. Sruthy KS, Shukla L, Kundu A, Singh SK, Abdulrahman Alodaini H, Hatamleh AA, et al. Effect of microbial consortium constructed with lignolytic ascomycetes fungi on degradation of rice stubble. *JoF*. (2023) 9:567. doi: 10.3390/jof9050567

127. Chander AM, Singh NK, Venkateswaran K. Microbial technologies in waste management, energy generation and climate change: implications on earth and space. *J Indian Inst Sci*. (2023) 103:833–8. doi: 10.1007/s41745-023-00388-3

128. Fotschki J, Ogrodowczyk AM, Wróblewska B, Juśkiewicz J. Side streams of vegetable processing and its bioactive compounds support microbiota, intestine milieu, and immune system. *Molecules*. (2023) 28:4340. doi: 10.3390/molecules28114340

129. Puentes-Téllez PE, Falcao Salles J. Construction of effective minimal active microbial consortia for lignocellulose degradation. *Microb Ecol*. (2018) 76:419–29. doi: 10.1007/s00248-017-1141-5

130. Mendes IV, Garcia MB, Bitencourt ACA, Santana RH, Lins PDC, Silveira R, et al. Bacterial diversity dynamics in microbial consortia selected for lignin utilization. *PloS One*. (2021) 16:e0255083. doi: 10.1371/journal.pone.0255083

131. Zhao Y, Li X, Li Y, Bao H, Xing J, Zhu Y, et al. Biochar acts as an emerging soil amendment and its potential ecological risks: A review. *Energies*. (2022) 16:410. doi: 10.3390/en16010410

132. Gladkov GV, Kimeklis AK, Afonin AM, Lisina TO, Orlova OV, Aksenova TS, et al. The structure of stable cellulolytic consortia isolated from natural lignocellulosic substrates. *IJMS*. (2022) 23:10779. doi: 10.3390/ijms231810779

133. Xiao L, Lichtfouse E, Lichtfouse E, Kumar PS, Wang Q, Liu F. Biochar promotes methane production during anaerobic digestion of organic waste. *Res Square*. (2021) 19. doi: 10.21203/rs.3.rs-298852/v1

134. Dsouza A, Price GW, Dixon M, Graham T. A conceptual framework for incorporation of composting in closed-loop urban controlled environment agriculture. *Sustainability*. (2021) 13:2471. doi: 10.3390/su13052471

135. Afraz MT, Xu X, Adil M, Manzoor MF, Zeng X-A, Han Z, et al. Subcritical and supercritical fluids to valorize industrial fruit and vegetable waste. *Foods*. (2023) 12:2417. doi: 10.3390/foods12122417

136. Sumfleth B, Majer S, Thrän D. Recent developments in low iLUC policies and certification in the EU biobased economy. *Sustainability*. (2020) 12:8147. doi: 10.3390/su12198147

137. Nikravech M. Perspective—Evaluating the impact of food waste reduction policies. *Front Sustain Food Syst*. (2023) 7:1170226. doi: 10.3389/fsufs.2023.1170226

138. Vanholme B, Desmet T, Ronsse F, Rabaey K, Breusegem FV, Mey MD, et al. Towards a carbon-negative sustainable bio-based economy. *Front Plant Sci*. (2013) 4:174. doi: 10.3389/fpls.2013.00174

139. Mayer A, Haas W, Wiedenhofer D, Krausmann F, Nuss P, Blengini GA. Measuring progress towards a circular economy: A monitoring framework for economy-wide material loop closing in the EU28. *J Ind Ecol*. (2019) 23:62–76. doi: 10.1111/jiec.12809

140. Lehn F, Schmidt T. Sustainability assessment of food-waste-reduction measures by converting surplus food into processed food products for human consumption. *Sustainability*. (2022) 15:635. doi: 10.3390/su15010635

141. Falcone G, Stillitano T, Iofrida N, Spada E, Bernardi B, Gulisano G, et al. Life cycle and circularity metrics to measure the sustainability of closed-loop agri-food pathways. *Front Sustain Food Syst*. (2022) 6:1014228. doi: 10.3389/fsufs.2022.1014228

142. Domenech T, Borrion A. Embedding circular economy principles into urban regeneration and waste management: framework and metrics. *Sustainability*. (2022) 14:1293. doi: 10.3390/su14031293